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Optimizing the Efficiency of Rock Disintegration by Liquid Jets

Terraspace Inc.

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OPTIMIZING THE EFFICIENCY OF ROCK DISINTEGRATION BY LIQUID JETS

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William C. Cooley
Paul E. Brockert

TERRASPACE INCORPORATED
304 North Stonestreet Ave.
Rockville, Maryland 20850

FINAL REPORT

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Prepared by
Terraspace Incorporated
304 North Stonestreet Ave.
Rockville, Maryland 20850

William C. Cooley
Principal Investigator
Phone (301) 424-0090

Paul E. Brockert
Project Engineer
Phone (301) 424-0090

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13. ABSTRACT

This report covers experimental research in producing craters in large Barre granite samples by the use of pulsed high pressure water jets. Two exponential nozzles of the type developed by Prof. Voitsekhovsky in the USSR were used: A Russian-made nozzle with an exit diameter of 7.16 mm and an American-made nozzle with an exit diameter of 6 mm. Water was expelled from the nozzles by firing steel pistons from a nitrogen gas gun of 3.25 inch bore.

Best results were obtained with the American nozzle, using vacuum in the nozzle prior to each shot. Jet stagnation pressures up to 255,000 psi were achieved. Crater volumes up to 300 cc were obtained in a single pulse, yielding a specific energy of 223 J/cc. The data show a trend toward lower specific energy as the jet pressure was increased from 113,000 to 255,000 psi. Higher pressures were not achieved because of water cavitation at the high piston velocities required with the small bore gas gun.

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1.0 OBJECTIVES AND SCOPE

The objective of this experimental research program was to extend the study of the relationship between the damage to hard rock and the jet stagnation pressure of a pulsed water jet system which had been conducted under a prior contract (ref.1). It was also an objective to determine the effect of multiple jet pulses to the same target area and to determine the optimum spacing between shots to obtain most effective rock disintegration. It was planned that jet stagnation pressures should range from 100,000 to 800,000 psi. Rock samples were 2'X2'X2' or larger, to attain craters in the face only, without splitting the samples.

2.0 INTRODUCTION

Research on the use of pulsed high pressure water jets has shown that they provide a promising method for rock excavation. Professor B. V. Voitsekhovsky in the Soviet Union was one of the first to conduct research of this type, but details were never published. Under a prior contract (ref.1), Terraspace Inc. conducted research on rock breakage using an exponential nozzle which was imported from Professor Voitsekhovsky. The results established that the specific energy for cratering of rock is greatly reduced by increasing the jet stagnation pressure from about 1.4 to 4 times the compressive strength of the rock. These tests were made with ambient air in the nozzle prior to each shot, which prevented attainment of velocities above 1450 m/sec (4400 ft/sec), corresponding to a jet stagnation pressure of 1050 MN/m^2 (150,000 psi). A few test shots were made with a vacuum in the nozzle which permitted attaining a jet velocity up to 1800 m/sec (5500 ft/sec) and a pressure of 1600 MN/m^2 (227,000 psi). However, there were insufficient data with vacuum to establish a trend. Therefore, the present program was conducted in an attempt to extend the data to higher pressures and to use both the Russian nozzle and an American-made nozzle having a larger area ratio. As discussed later, considerable difficulty was encountered with the experimental equipment and the highest jet velocity measured in a total of 33 test shots was 2020 m/sec (6150 ft/sec), corresponding to a pressure of 1800 MN/m^2 (255,000 psi).

3.0 EXPERIMENTAL EQUIPMENT

All tests in this program were made using rock samples of Barre granite at least 2'X2'X2'. The stand-off distance in all but 2 of the tests was between 10 and 13 centimeters. The granite face was rough-cleaved and was generally normal to the jet axis within 15 degrees.

The initial series of 16 test shots were made using the Russian nozzle and a gas gun test rig as described in Ref. 1. The final 17 shots were made using the American nozzle which was manufactured by the Speco Division of Kelsey-Hayes. The nozzle design is shown in Fig. 1. Its development is reported in Ref. 2. The nozzle exit diameter was 6 mm as compared to an exit diameter of 7.16 mm for the Russian nozzle. The calculated maximum wall pressure allowable in the American nozzle was 200,000 psi as compared to 180,000 psi for the Russian nozzle. The theoretical maximum jet stagnation pressure is four times larger than the maximum wall pressure.

The Russian nozzle was connected to the Section 1 by means of a cylindrical adapter, whereas the American nozzle was threaded directly to Section 1, thereby preserving the approximately exponential variation of area with length.

A variety of piston designs were used during the test program in an attempt to achieve improved nozzle performance without producing excessively high pressure spikes in the entrance chamber. The piston designs were:

A. 3.0kg - flat nose - Fig. 2
B. 6.2kg - flat nose - Fig. 3
C. 3.7kg - conical nose (1-1/2 inch high) - Fig.4
D. 5.55kg - conical nose (1-1/2 inch high) - Fig.5
E. 3.7kg - conical nose (1/2 inch high) - Fig.6

The theoretically correct piston mass was 2.8 kg for use with both the Russian and American nozzles. However, the effect of leakage around the piston, especially in the case of the conical-nose pistons, requires a larger mass to compensate for this energy loss.

Special plastic packages were molded to hold water in the inlet Section 1 of the nozzle. Each package (see Fig. 7), had a hemispherical cap of 5.4 mm diameter located

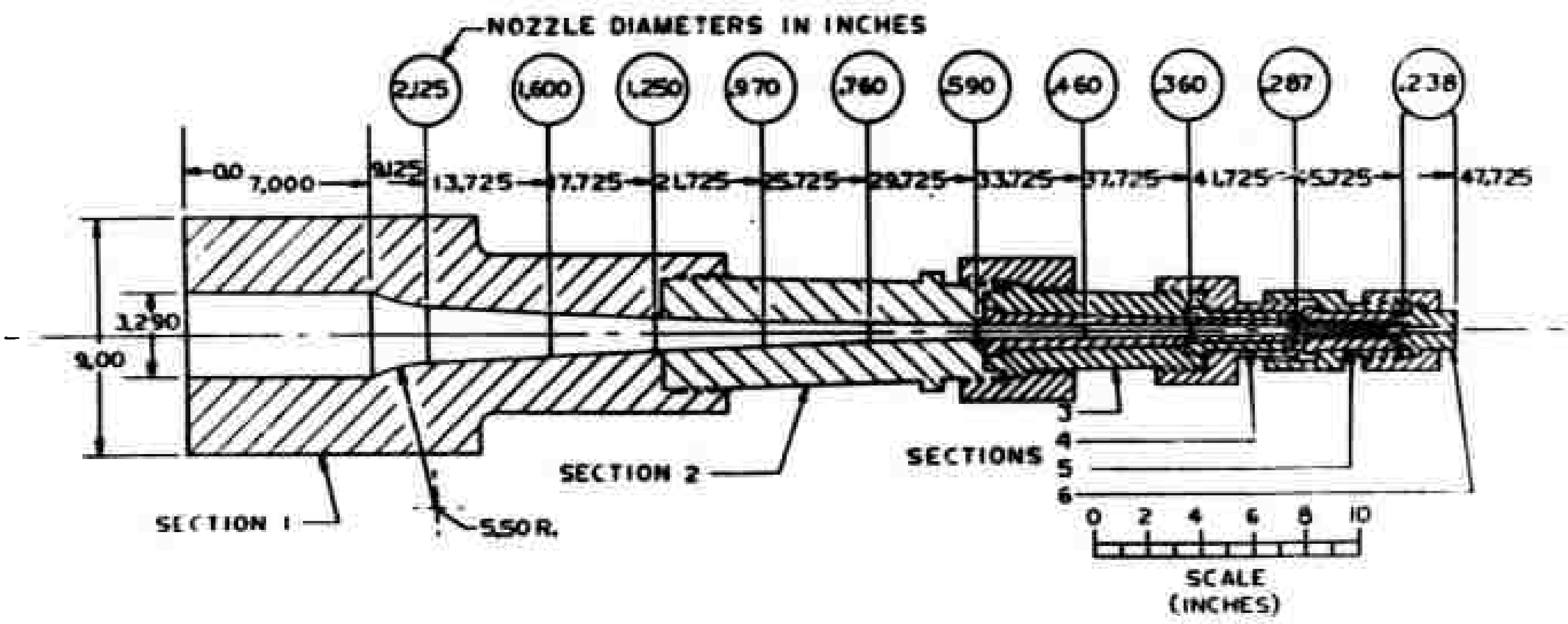
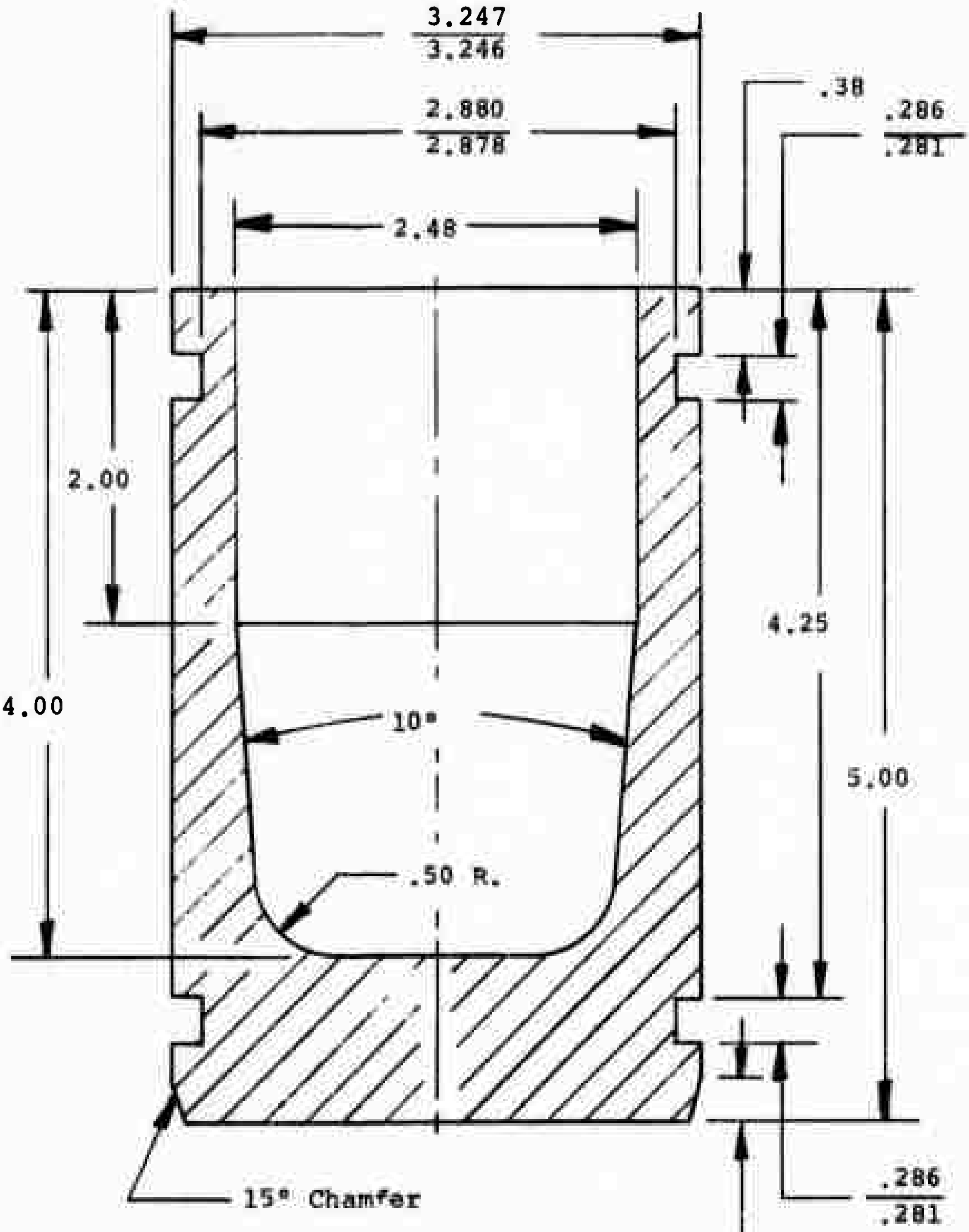
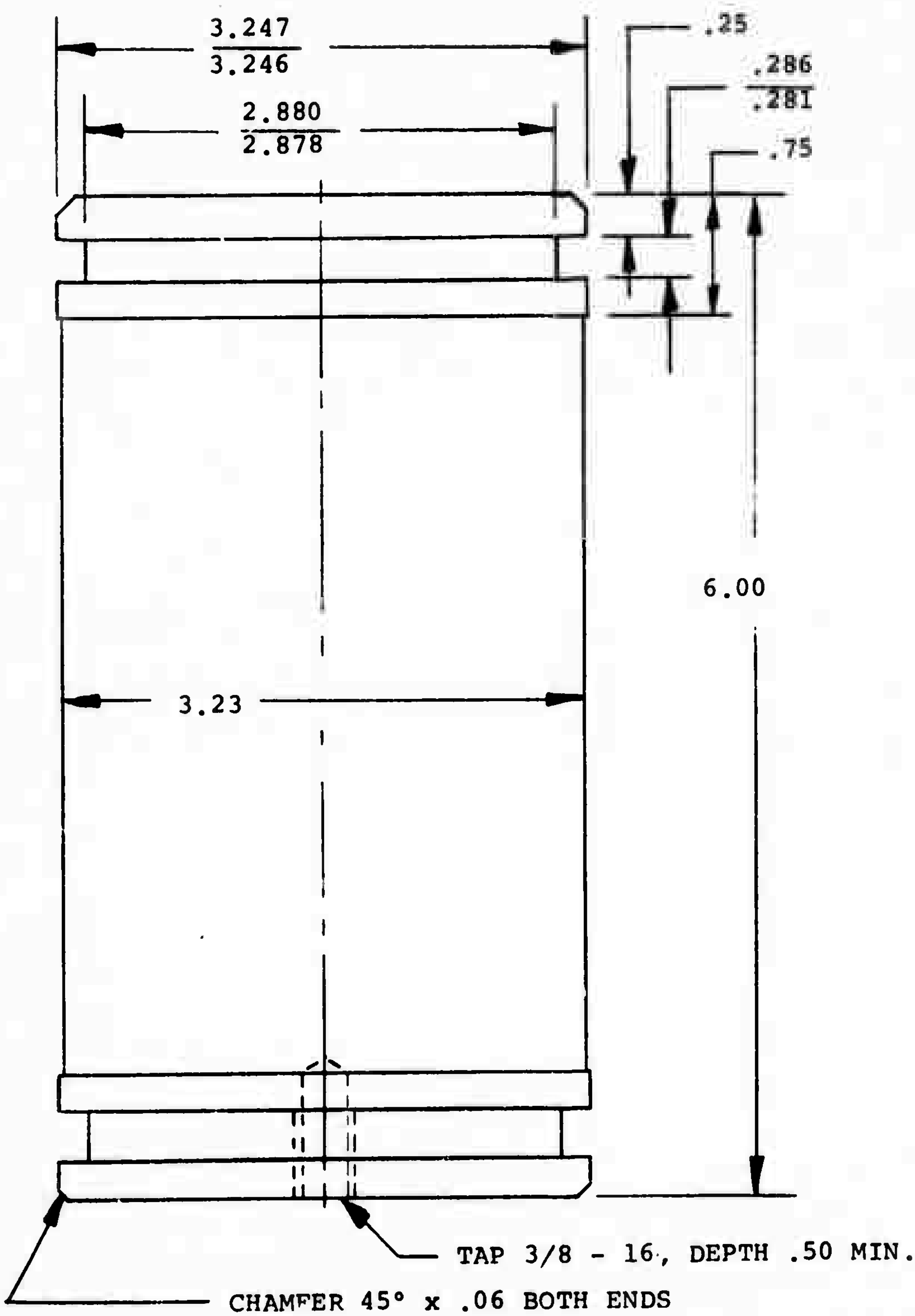


Figure 1. Drawing of American Design Nozzle



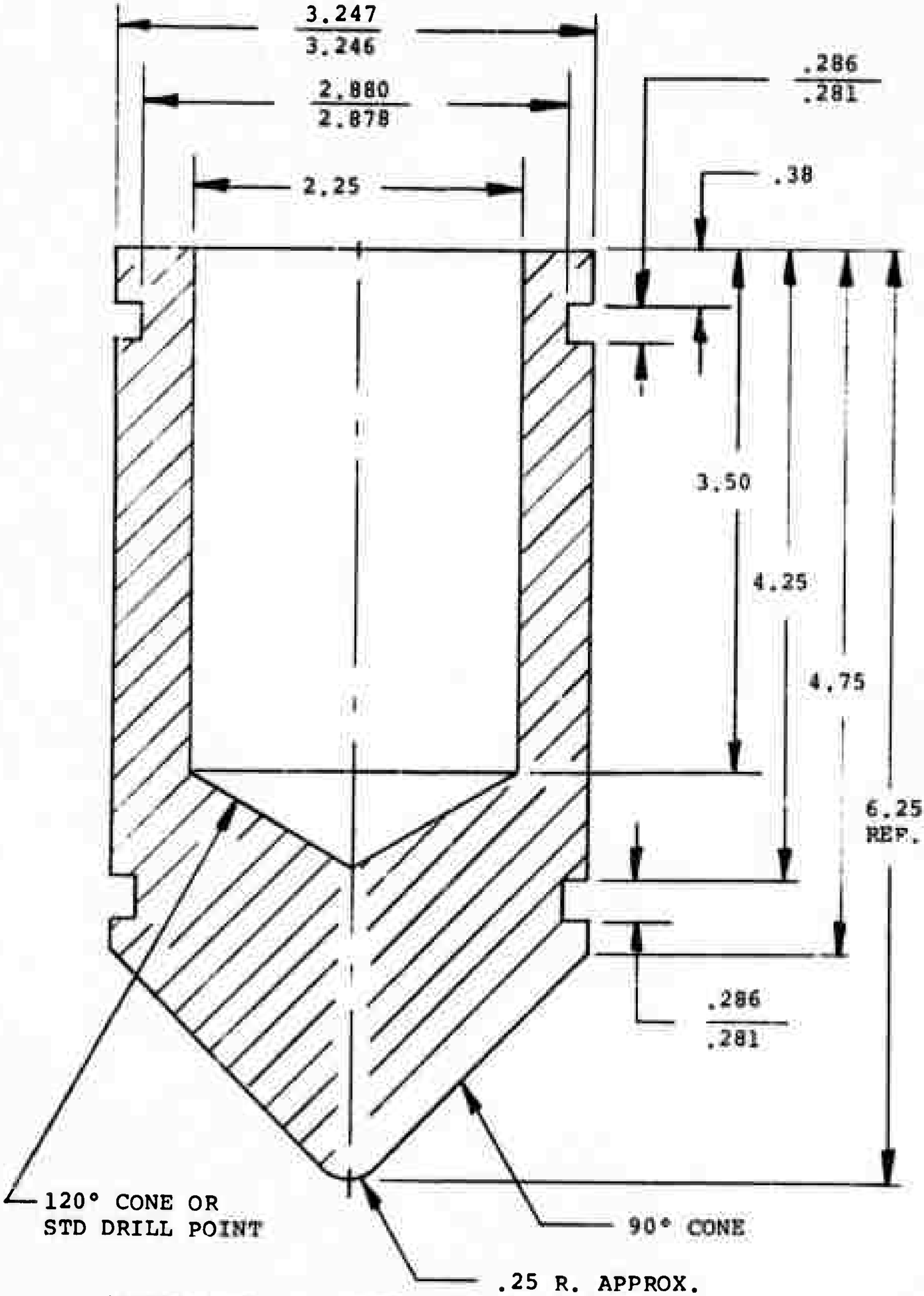
(Dimensions in inches. Weight 3.0 Kg.)

FIG. 2. PISTON DESIGN A



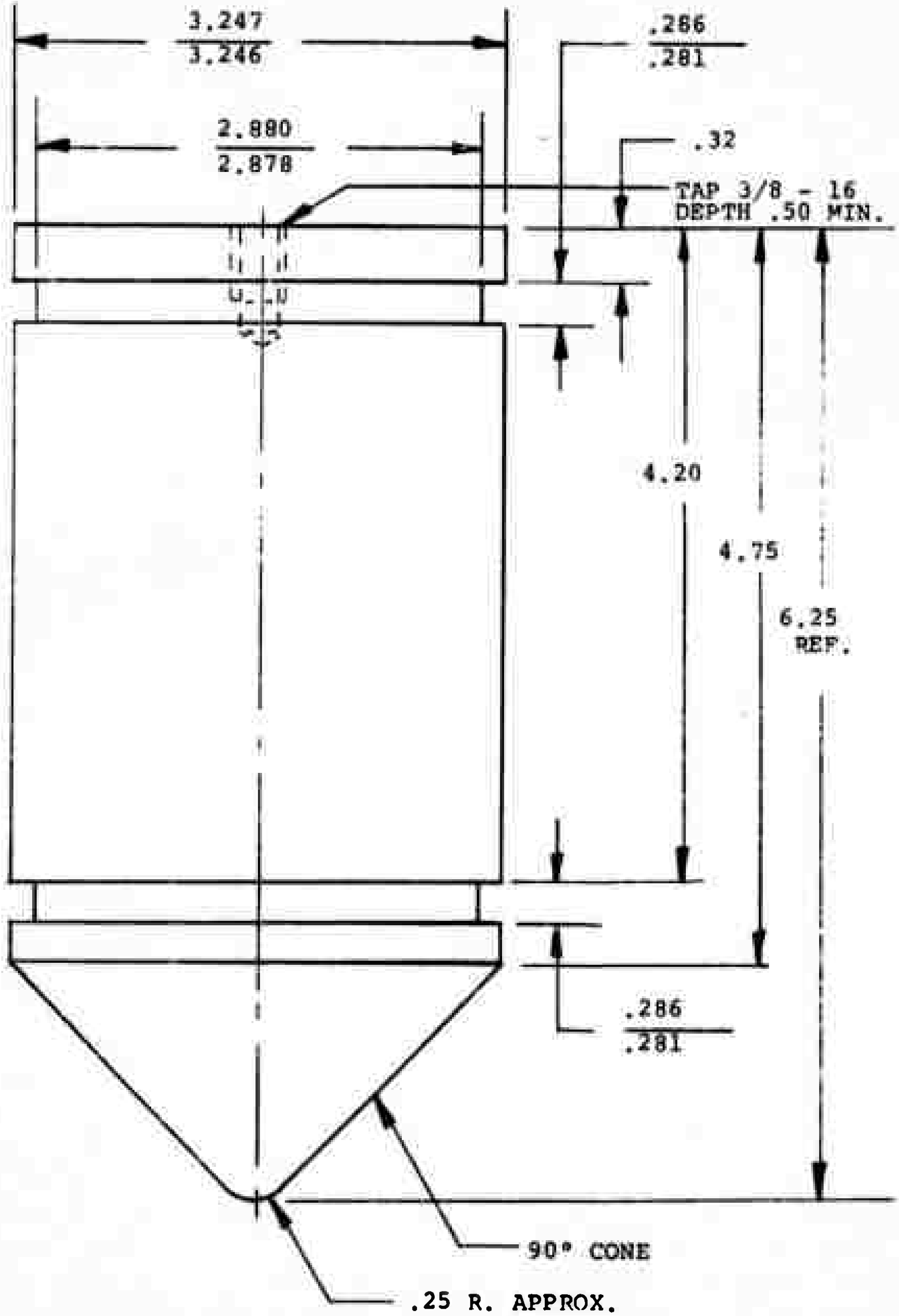
(Dimensions in inches. Weight 6.2 Kg.

FIG. 3. PISTON DESIGN B



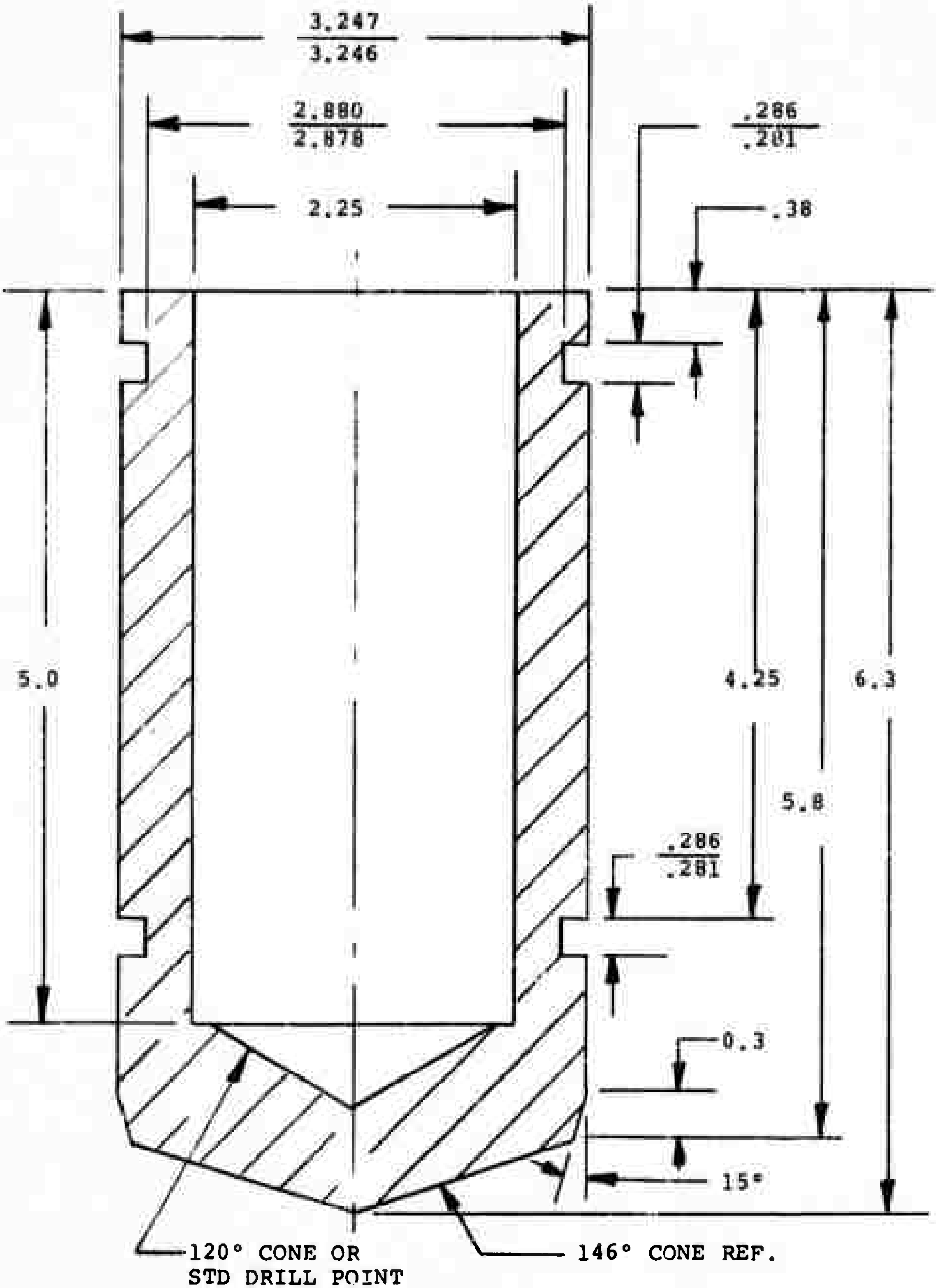
(Dimensions in inches. Weight 3.7 Kg.)

FIG. 4. PISTON DESIGN C



(Dimensions in inches. Weight 5.55 Kg.)

FIG. 5. PISTON DESIGN D



(Dimensions in inches. Weight 3.7Kg.)

FIG. 6. PISTON DESIGN E

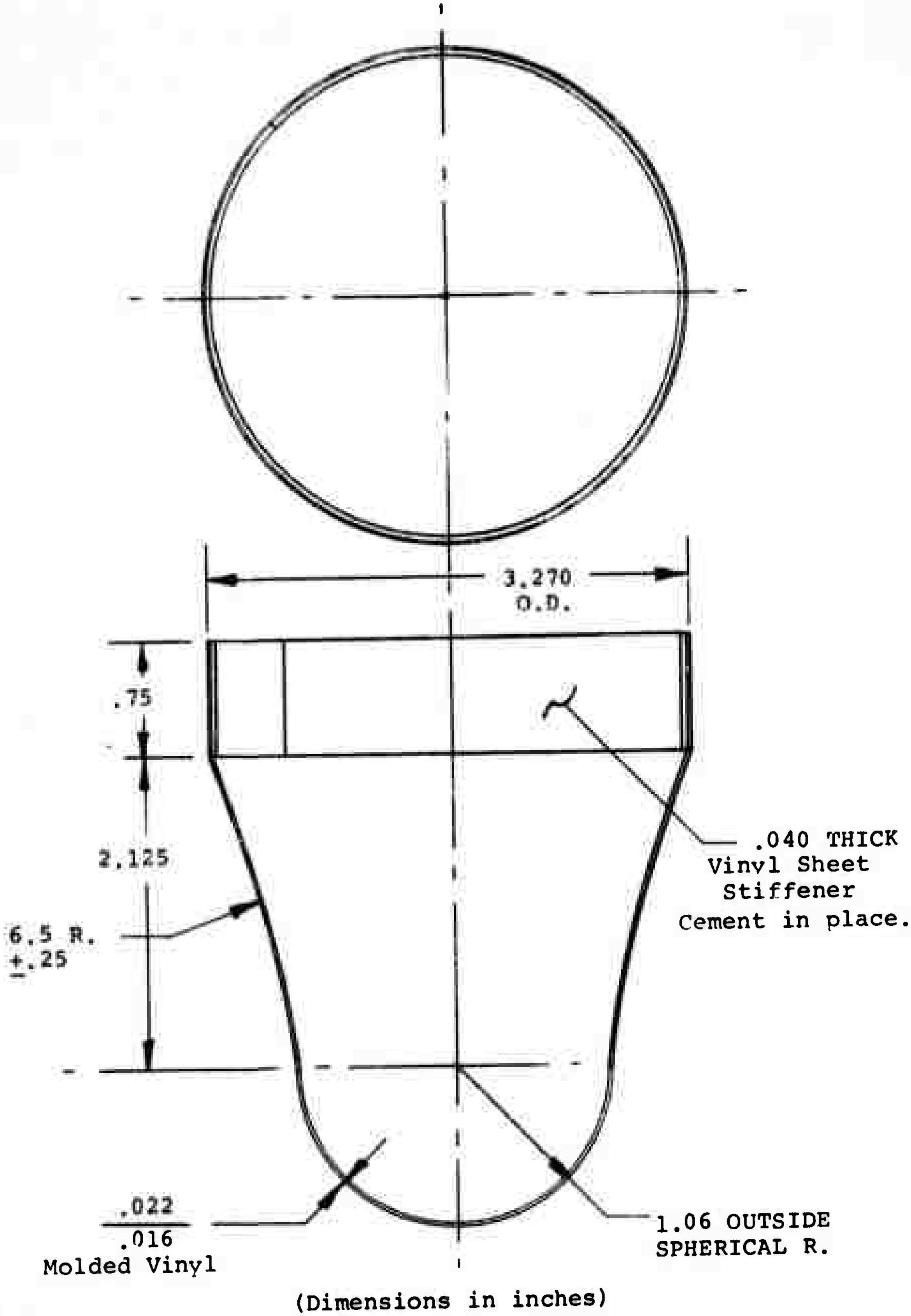


FIG. 7. WATER PACKAGE

at the nozzle throat. The plastic wall thickness of 0.5 mm was sufficient to permit pulling a vacuum in the nozzle without failure of the plastic. The plastic surface was scribed with cross-shaped grooves to achieve splitting and release of water when the first water shock wave arrived after piston impact.

The water package was closed at the entrance end by a sheet of plastic which was sheared by piston impact. The barrel of the nitrogen gas gun was also sealed with a plastic sheet and evacuated to a pressure below 10 Torr in all cases in order to minimize the jet of air which is expelled from the barrel ahead of the piston. A separate vacuum pump was used to evacuate the nozzle.

Fig. 8 shows a photograph of the American nozzle and a rock sample.

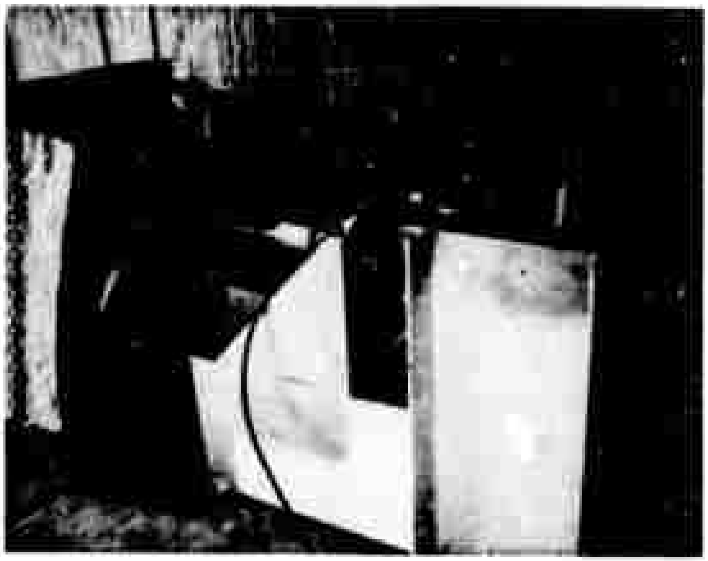


FIG. 8. PHOTOGRAPH OF AMERICAN NOZZLE AND ROCK SAMPLE

4.0 INSTRUMENTATION

The instrumentation used has been described in Ref.1. It included measurement of piston velocity, chamber pressure at the nozzle inlet, and jet velocity. Piston velocity was measured from the upper trace of each oscillogram by determining the time for the piston to traverse a distance of 12.06 cm between two electrical contacts at the end of the gas gun barrel. The oscilloscope trace was triggered by the first of these two contacts. The horizontal sweep speed in all cases was 0.5 msec per centimeter. Chamber pressure was recorded on the lower trace of each oscillogram. The vertical amplitude was 37,700 psi per cm of vertical displacement. Jet velocity was determined by using a microsecond timer to measure the time between breakage of two pencil leads located 3.0 cm apart at the nozzle exit. One change was made which provided an electrical signal to the upper channel of the oscilloscope at the time of breakage of the first pencil lead located 2 cm from the nozzle exit. This permitted determination of the time required to fill the nozzle after piston impact.

The gas gun breech was loaded with compressed nitrogen at pressures from 600 up to 1250 psi before each shot. The nozzle pressure prior to each shot was measured by means of a thermocouple vacuum gage and was below 0.35 Torr in all cases when vacuum was used, which was all shots except shots 1, 2, 3, 5, 6 and 11. The nozzle was sealed at the exit by a plastic disk which was perforated by the water.

After each test shot, the crater volume was measured by filling the crater with putty, then measuring the putty volume in a graduated breaker.

5.0 TEST RESULTS

5.1 General Discussion

Test results are given in Table 1. Test shots #1 and 2 were made with flat-faced pistons. These produced pressure spikes in the entrance chamber of 113,000 psi for the 3.0 kg piston and 95,000 psi for the 6.2 kg piston at nitrogen pressures of only 600 psi. Therefore,

there was concern that the entrance chamber might be damaged by excessive pressure as the piston energies were later increased. This problem was discussed by W. C. Cooley during a personal visit with Professor B. V. Voitsekhovsky in Novosibirsk, Siberia, in July 1972. He confirmed our expectation that the strong shock waves could also cause water spray to be ejected into the nozzle ahead of the advancing liquid front which would cause a decrease in performance. The basic reason for the problem is that we used a piston diameter of only 3.25 inches instead of 6.3 inches in the earlier Russian experiments. Therefore, we had to use piston velocities a factor of 3.75 higher in order to produce equivalent volume flow rate into the nozzle. This resulted in strong shock waves which reflect as tension waves from the forward end of the water and produce cavitation phenomena in the water. (The water flies off like a ball from a bat).

Professor Voitsekhovsky suggested that a solution might be achieved by using a conical nose on the piston in order to cause a slower build-up of pressure in the chamber. In theory, the height of the cone should be long enough that the time to enter the water fully is long compared to the time for sound waves to traverse the water volume and return. However, this was not possible with our small bore (3.25 inch) test rig because the theoretical piston stroke to fill the nozzle was only four inches. Therefore, a long cone would cause excessive energy loss due to radial expulsion of water as the cone entered the chamber. A compromise solution was tried using piston design C (Fig.4) which had a cone height of 1.5 inches. In this case, at a piston velocity of 600 ft/sec, the cone would enter in a time of 0.2 msec, whereas the transit-time for a round trip of sound waves through the 9 inch long water volume was 0.3 msec. Although this did not meet the desired criterion, it at least helped to reduce the strength of shock waves produced. Therefore, all shots 3 through 33 (except for shots 10, 11 and 12), were made with conical nose pistons. In shots 3 through 9, there was some indication that the amplitude of the initial pressure spikes was at least statistically lower than it would have been with flat pistons at the same piston velocity. However, in every test shot there is evidence from the pressure oscillogram that after the first impact

TABLE I. TEST RESULTS ON BARRE GRANITE SAMPLES

SHOT No.	N_2 Press. Psi	NOzzle	Press. in Nozzle Torr	Piston Design	Piston Mass Kg.	Piston Velocity ft/sec	Jet Velocity ft/sec	Standoff Distance Cm.	Piston Energy kJ.	Crater Volume cc	Specific Energy J/cc	Jet Press. ksi	Specific Press.	Piston Damage?
1	600	Russ.	Atm	A	3.0	528		15	39	0	∞	-	-	
2	600		Atm	B	6.2	377	3510	10	41	0	∞	83	2.77	
3	700		Atm	C	3.7	528		15	47	0	∞	-	-	
4	700		0.05	C		528	1310	10	47	120	390	11.5	0.38	
5	750		Atm	C		528	1310	10	47	0	∞	11.5	0.38	
6	800		Atm	C		528		10	47	2	23500	-	-	
7	800		0.05	C		528	1610	10	47	23	2050	17.5	0.58	
8	850		0.05	C		550	2600*	10	51	57	895	45.5	1.52	
9	900		0.08	C		610	3080	10	63	20	3150	64	2.13	
10	700		0.20	B	6.2	440	4480	10	55.5	5	11100	135	4.50	yes
11	700		Atm	B	6.2	417	2810	10	50	1	50000	53	1.77	
12	750		0.08	B	6.2	417	4680	10	50	3	16700	147	4.90	yes
13	800		0.08	D	5.55	440	3800*	10	50	240	210	97	3.24	yes
14	800		0.05	D		417	3790	10	45	10	4500	97	3.24	yes
15	850		0.05	D		467	5180	10	56	65	860	180	6.00	yes
16	900		0.05	D		467	4920	10	56	62	900	163	5.44	yes
17	600	Amer.	0.08	D		396	4100	10	40.5	5	8100	113	3.77	yes
18	700		0.05	D		440	4680	10	50	23	2170	147	4.90	yes
19	800		0.1	D		450	5470	10	52	33	1570	200	6.67	yes
20	900		0.1	D		496	5800*	10	63	45	1400	226	7.53	yes
21	900		0.1	D		496	5800	10	63	30	2100	226	7.53	yes
22	900		0.05	C	3.7	610	5470	10	64	14	4570	200	6.67	yes
23	950		0.1'	C	3.7	630	5800	10	67	300	223	226	7.53	
24	1000		0.25	C	3.7	720	6150	10	87.5	32	2730	255	8.50	
25	950		0.27	E	3.7	610	5800	10	64	10	6400	226	7.53	yes
26	1000		0.24	E		593	5900*	10	60	62	970	234	7.80	yes
27	1050		0.07	E		610	5800	11.5	64	30	2130	226	7.53	
28	1100		0.08	E		660	6150	11.5	75	42	1780	255	8.50	
29	1150		0.08	E		640	6100*	10	70.5	95	740	250	8.33	yes
30	950		0.10	E		575	5800*	11.5	57	22	2600	226	7.53	yes
31	1200		0.20	E		640*	6150*	11.5	50.5	220	320	255	8.50	yes
32	1200		0.20	E		640	6150*	12.7	70.5	58	1220	255	8.50	yes
33	1250		0.35	E		660*	6150	12.7	75	52	1440	255	8.50	yes

*NOTE: VALUES OBTAINED BY INTERPOLATION OR EXTRAPOLATION ON N_2 FIRE PRESSURE

by the piston, there is a period of about 0.5 msec or more with essentially zero pressure in the chamber indicating that the water has separated from the piston and is coasting into the nozzle. This occurs because the first shock wave sweeps through the water package and reflects as a tension wave from its forward surface. When the tension wave returns to the piston face, in about 0.3 msec after impact of the piston, a vapor cavity at very low pressure (the vapor pressure of water) is formed, the cavity grows, and the liquid slug "flies off" like a ball from a bat. The water slug coasts into the nozzle and its rear surface decelerates. In most cases, the piston again makes contact before the nozzle is full and then makes a series of impacts at the resonant frequency of the piston, which was typically about 8000 cps. These later impacts often continued even after the nozzle was full. This is undesirable because it indicates that the full energy of the piston was not expended during the unsteady acceleration phase of filling the nozzle.

Beginning with Shot 13, it was evident that the piston would occasionally hit the entrance to Section 1 a glancing blow, which made it impossible to determine the actual energy imparted to the water and which often damaged the piston sufficiently to prevent reuse. This was believed to be caused by one or both of the following problems: (1) Asymmetry of the plastic face of the water package at the time of cone entry, causing radial hydrodynamic forces which deflected the piston while the cone entered the chamber, and (2) Deflections of the gun barrel during firing which deflected the piston.

Attempts were made to alleviate these problems by assuring initial symmetry of the entrance closure on the water package and by moving the nozzle closer to the gun muzzle (beginning with shot 6). Also, beginning with shot 25, piston design E with a decreased cone height of 0.5 inch was used in an attempt to avoid hydrodynamic deflection. However, these efforts did not completely cure the problem, which persisted throughout the program.

It appears possible that the problem is also associated with the jet of air ejected from the gun muzzle ahead of the piston which may produce unsymmetrical distortion of the plastic closure of the water package prior to entry of the conical piston.

The most clear-cut cases in which piston impact on Section 1 evidently detracted from rock breakage were shots 14 and 25.

5.2 Tests with Air in the Russian Nozzle

Tests with air at atmosphere pressure in the Russian nozzle (Shots 1, 2, 3, 5, 6, and 11), with nitrogen fire pressures of 600 to 800 psi produced only negligible damage to the granite samples (crater volumes less than 2 cc). Comparing shots 3 and 4, it is seen that by using vacuum in the nozzle and by decreasing the standoff distance from 15 to 10 cm, the crater volume increased from essentially zero to 120 cc. Tests 5, 6 and 11, with air in the nozzle at a standoff of 10 cm still showed only 0 to 2 cc water volume. Therefore, it was concluded that vacuum in the nozzle was extremely important at these low piston energies (35,000 ft-lbs, or less), in order to achieve rock fracture. Therefore, shots 12 through 33 were all made with the nozzle evacuated to a pressure of less than 0.35 Torr.

5.3 Tests with Vacuum in the Russian Nozzle

Ten shots were made with vacuum in the Russian Nozzle. (Shots 4, 7, 8, 9, 10, 12, 13, 14, 15 and 16). Three of these shots were completely successful (#4, 7 and 9), in that the piston apparently did not lose energy by hitting the entrance of Section 1 and a presumably valid jet velocity was measured. These shots 4, 7 and 9 yielded crater volumes of 120 cc, 23 cc and 20 cc, respectively.

Figure 9 shows the oscillogram for Shot 9 at a sweep speed of 0.5 msec per cm. On the upper trace, it is seen that the piston traversed the 12.06 cm spacing in 0.65 msec, corresponding to a velocity of 610 ft/sec. On the lower trace, the first pressure spike had an amplitude of 180,000 psi. The time to fill the nozzle after this first impact was 0.8 msec. However, several pressure pulses occurred after the nozzle was full. Fig. 10 shows a photograph of the crater for shot 9 which had a volume of 20 cc.

Shot 8 also produced a good crater, although a jet velocity measurement was not directly obtained. However, the jet velocity was obtained by interpolation from Fig. 16. Fig. 11 shows the oscillogram for Shot 13 using the heavier piston design D. It is seen that more of the piston energy was delivered before the nozzle filled and the specific energy was greatly reduced as compared to Shot 9. The crater volume for shot 13 was anomalously large, especially in view of the fact that the piston was damaged by impact on the entrance to the nozzle.

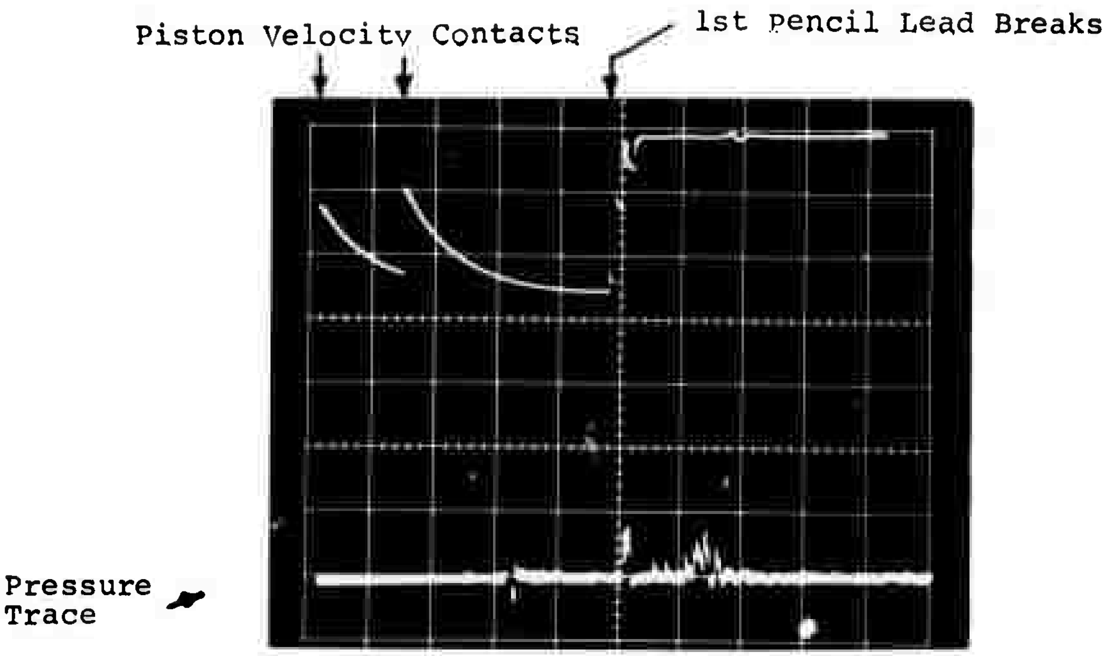


FIG. 9. OSCILLOGRAM FOR SHOT 9 - VACUUM IN RUSSIAN NOZZLE

Piston design C	Specific Energy = 3150 J/cc
Piston Energy = 63,000 J	Jet velocity = 3080 ft/sec
Crater Volume = 20cc	Jet pressure = 64,000 psi

FIG. 10. CRATER FOR SHOT 9

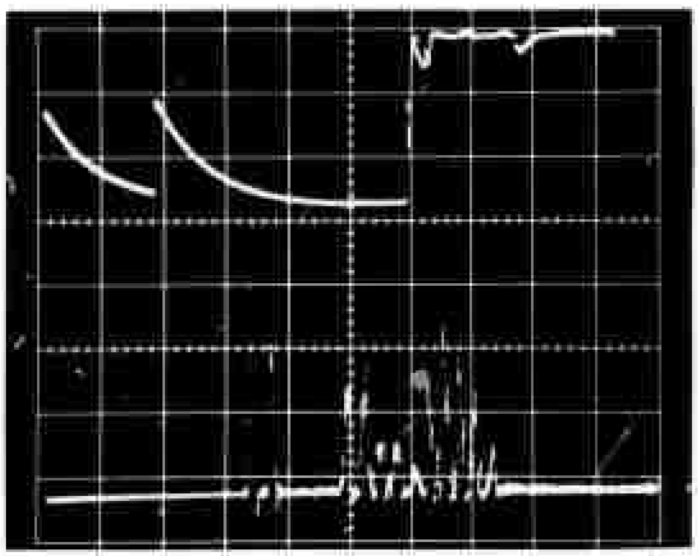


FIG. 11. OSCILLOGRAM FOR SHOT 13 - VACUUM IN RUSSIAN NOZZLE

Piston design D	Specific Energy = 210 J/cc
Piston Energy = 50,000 J.	Jet velocity = 3800 ft/sec
Crater Volume = 240 cc	Jet pressure = 97,000 psi

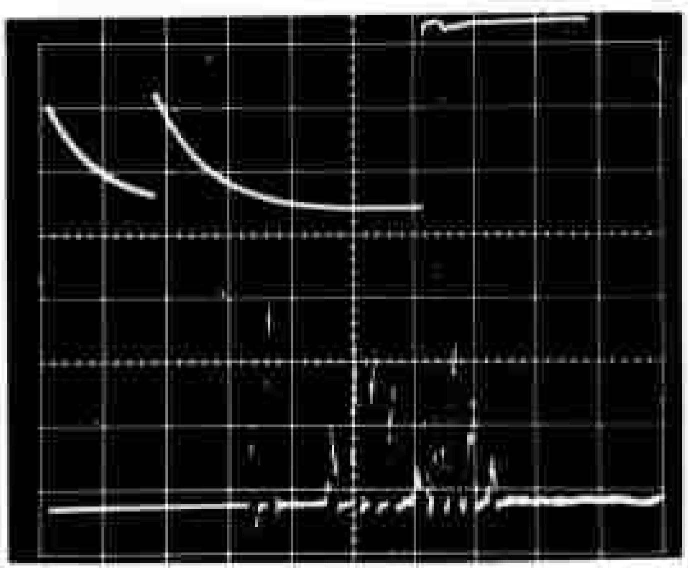


FIG. 12. OSCILLOGRAM OF SHOT 15 - VACUUM IN RUSSIAN NOZZLE

Piston Design D	Specific Energy = 860 J/cc
Piston Energy = 56,000 J.	Jet velocity = 5180 ft/sec
Crater Volume = 65cc	Jet pressure = 180,000 psi

Shots 15 and 16 produced good craters, even though the pistons were damaged on impact. Fig. 12 shows the oscillogram for Shot 15 which was very similar to Shot 16.

In these latter two cases, the specific energy calculated on the basis of initial piston energy was probably on the high side because of energy loss by impact on steel. It should also be noted that all values of specific energy are high because of water leakage through the clearance between piston and cylinder and also, in the case of conical pistons, because of energy loss by radial ejection of water during cone entry.

5.4 Tests with Vacuum in the American Nozzle

The American-made nozzle is described in Ref. 2. Seventeen shots (#17 through 33) were made with vacuum in the American nozzle and with conical nose pistons. Shots 17 through 21 were made with piston design C, shots 22 through 24 with design D, and shots 25 through 33 with design E. Four of these shots were completely successful (Shots 23, 24, 27 and 28). Six of these shots were partially successful (Shots 17, 18, 19, 21, 22 and 25), in that jet velocity measurements appeared reasonable, but some damage occurred to the piston. The calculated values of specific energy for these shots were then on the high side.

Shots 20, 26, 29, 30, 31 and 32 produced good craters, with some piston damage, but jet velocity records were not accurate. However, in these cases, jet velocity could be deduced by interpolation on plots of jet velocity vs. nitrogen fire pressure for each of the piston designs (see Fig. 17). In shots 31 and 33, no piston velocity measurement was obtained, but the value could be inferred from a plot of piston velocity vs N_2 fire pressure.

Fig. 13 shows a photograph of the crater from shot 23 which had a volume of 300 cc, the largest of any of the craters produced during the program. Fig. 14 shows the oscillogram for this shot. It shows several piston impacts occurring after the nozzle was completely filled.

Fig. 15 shows the crater for shot 24 which had a volume of only 32 cc alongside the larger crater from shot 23. Even though the energy and pressure were slightly higher for shot 24 than for shot 23, it produced a nearly 10 times smaller crater, showing a wide spread in statistical variation of the nozzle performance or the rock properties.

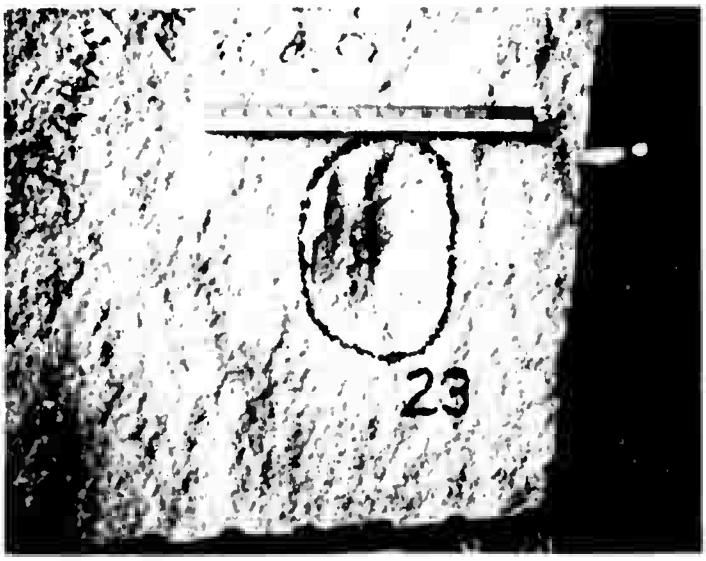


FIG. 13 CRATER FOR SHOT 23

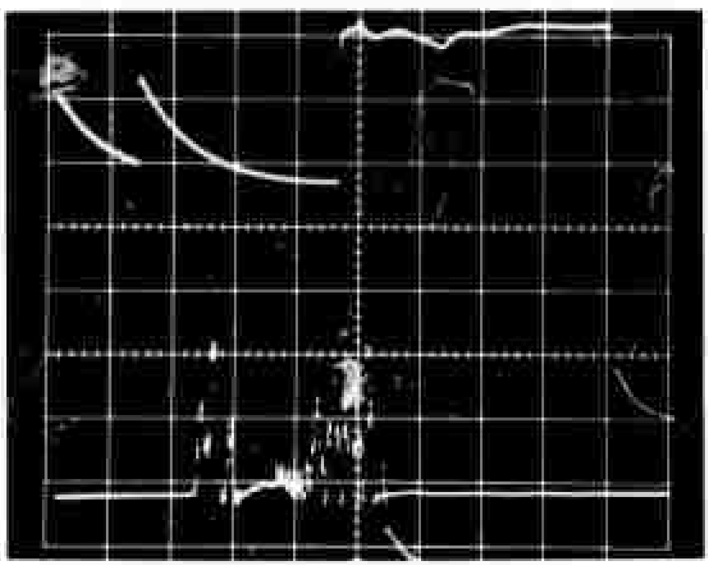


FIG. 14 OSCILLOGRAM FOR SHOT 23 - VACUUM IN AMERICAN NOZZLE

Piston Design D	Specific Energy = 223 J/cc
Piston Energy = 67,000 J	Jet velocity = 5800 ft/sec
Crater Volume = 300 cc	Jet pressure = 226,000 psi

FIG. 15. CRATERS FOR SHOTS 24 and 23

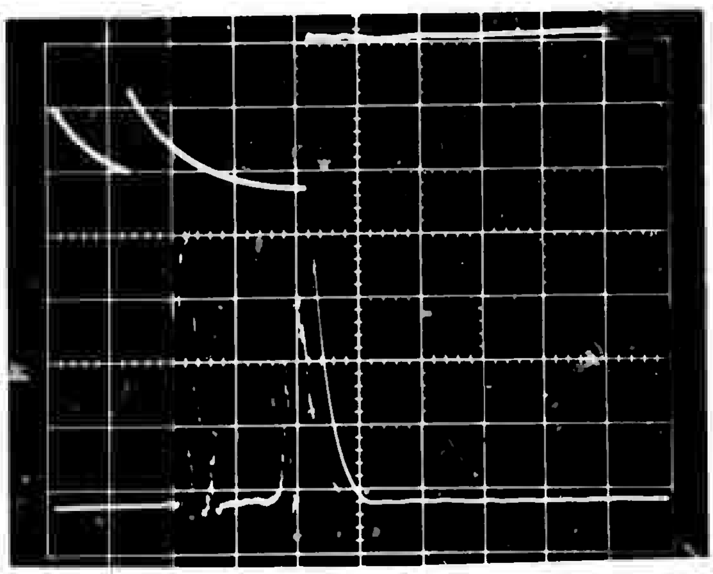


FIG. 16. OSCILLOGRAM FOR SHOT 28 - VACUUM IN AMERICAN NOZZLE

Piston Design E	Specific Energy = 1780 J/cc
Piston Energy = 75,000 J.	Jet velocity = 6150 ft/sec
Crater Volume = 42cc	Jet pressure = 255,000 psi

Fig. 16 shows the oscillogram for Shot 28 which was a successful shot using piston design E, the flat cone design. In this case it appears that only one piston impact occurred after the nozzle had filled and the pressure trace shows a smooth coast-down of pressure during the quasi-steady flow expansion of water through the filled nozzle.

6.0 DISCUSSION OF TEST RESULTS

6.1 Nozzle Performance

Fig. 17 shows a plot of the jet velocity achieved with vacuum in each nozzle as a function of nitrogen fire pressure, for various piston designs. It is seen that the highest jet velocity of 6150 ft/sec was achieved with the American nozzle and piston design E, which had the 1/2 inch high conical nose and a mass of 3.7 kg. The same jet velocity was achieved in shot 24 with piston design C, which had the same mass but a 1-1/2 inch high conical nose.

It is apparent from Fig. 17 that higher jet velocities were achieved with the American nozzle which had a smaller exit diameter than the Russian nozzle. However, the jet velocity seemed to reach an asymptotic limit of 6150 ft/sec as the nitrogen pressure was raised to 1250 psi. Failure to attain higher jet velocities is attributed to the cavitation and water separation problem which was caused by the high piston impact velocities which were necessary with this gas gun.

6.2 Rock Breakage

Fig. 18 shows values of specific energy plotted against specific pressure for all shots with vacuum in the two nozzles. It is seen that there is wide scatter in the data. The data obtained with the Russian nozzle at values of specific pressure below 3.24 appear to scatter too widely to permit correlation. These data should probably be eliminated because they were obtained at energies far below the theoretical design-point energy of the nozzle (73,000 J.). Under these conditions the piston generally bounces back after water impact and the flow into the nozzle is very erratic.

It is also noted that with the American nozzle, two data points were obtained with specific energy values of 223 and 320 J/cc which appear anomalously low compared to the bulk of the data. In one of these cases (Shot 31) it

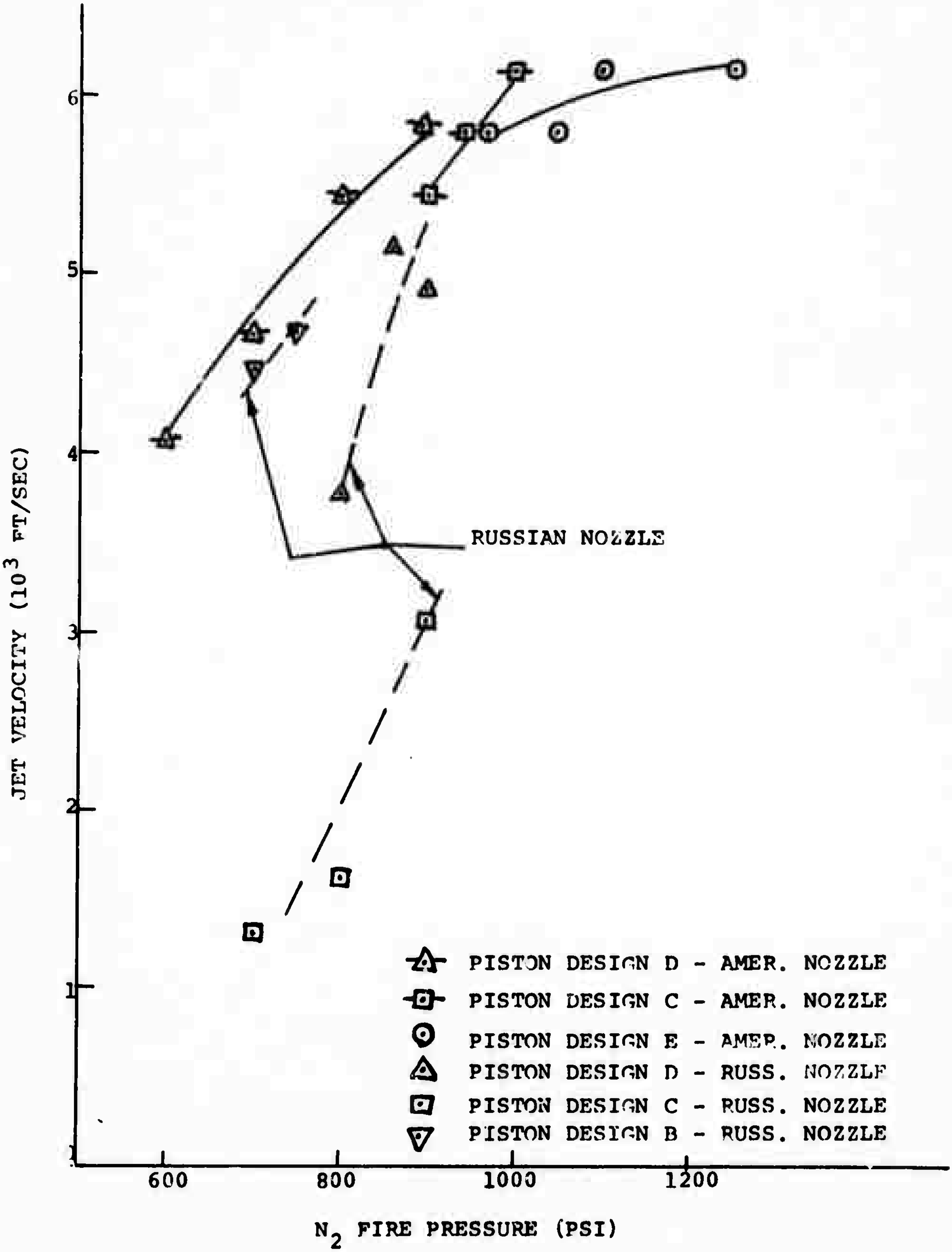
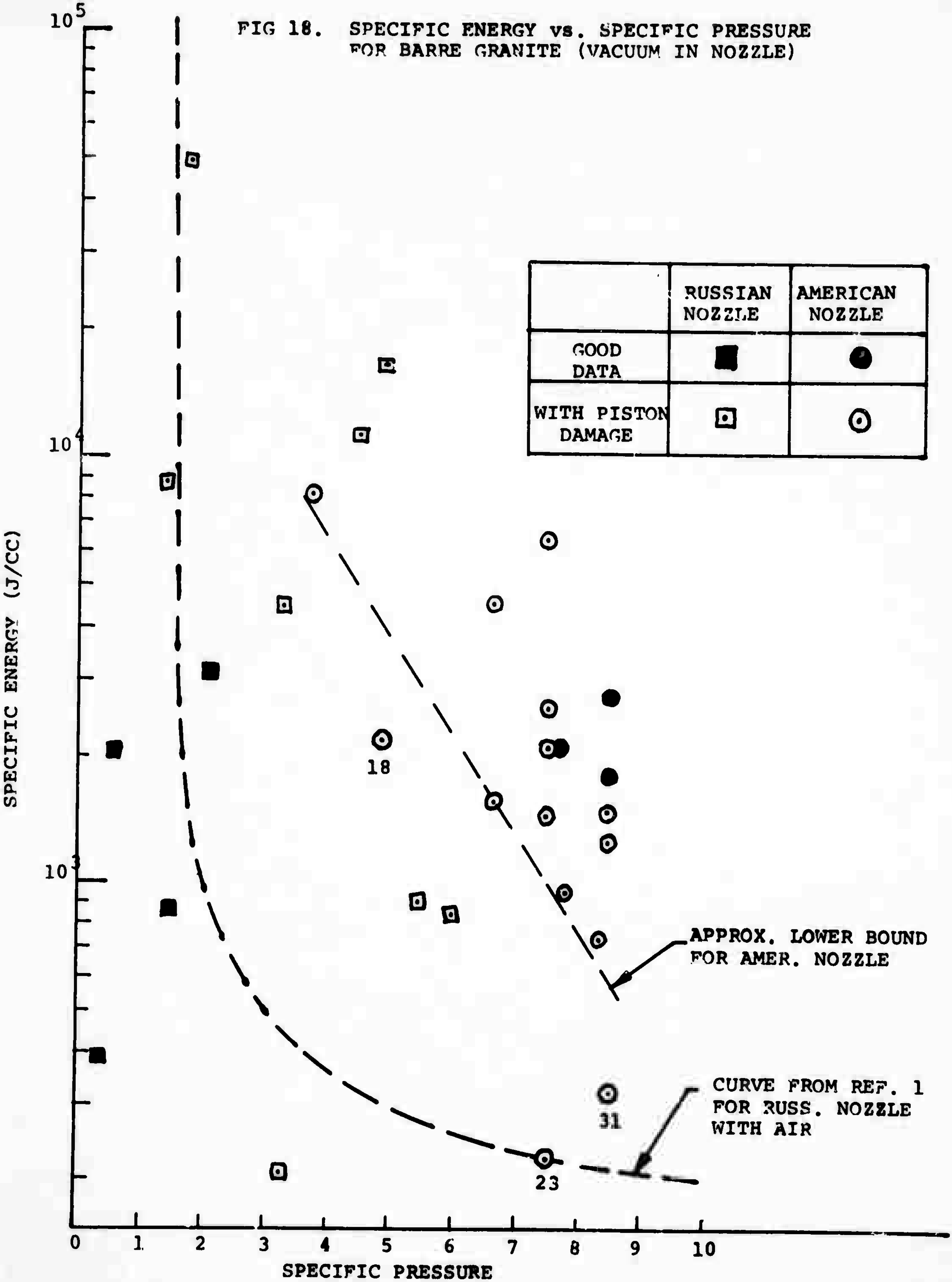


FIG. 17. JET VELOCITY vs. N_2 FIRE PRESSURE FOR VACUUM IN EACH NOZZLE

FIG 18. SPECIFIC ENERGY vs. SPECIFIC PRESSURE FOR BARRE GRANITE (VACUUM IN NOZZLE)



is known that the piston hit the cylinder which one would expect would decrease the crater volume.

Even if one eliminates Shots 23 and 31 from consideration, the remaining 15 data points taken with the American nozzle show a definite trend toward lower values of specific energy as the specific pressure is raised from 3.77 to 8.50. However, it would take great courage to draw a correlation line through these points. A dotted line has been drawn in Fig. 18 which indicates an approximate lower bound to the data for the American nozzle, excluding only Shots 18, 23 and 31.

Also shown in Fig. 18 is a curve of the data obtained in the prior research program (Ref.1), using air in the Russian nozzle. It is seen that nearly all the new data taken with vacuum in the American nozzle show values of specific energy higher than were previously obtained with air in the Russian nozzle. It is not clear why this is so, but some of the possible reasons are:

1. The new data were obtained mainly with conical pistons which waste kinetic energy as the cone penetrates the water package.

2. The use of vacuum may change the characteristics of the jet as it issues from the nozzle, possibly causing the jet to spread more rapidly and to be less effective.

3. Many of the tests produced piston damage by impact with the steel at the entrance to the pressure chamber, thereby wasting kinetic energy.

4. The American nozzle exit area was only 70% of that for the Russian nozzle, which would decrease the jet effectiveness for the same jet pressure.

7.0 CONCLUSIONS

1. The maximum jet velocity which was obtained with vacuum in the American-made exponential nozzle was 6150 ft/sec, corresponding to a jet stagnation pressure of 255,000 psi. Higher velocities were not obtainable using the available gas gun because it had too small a piston diameter (3.25 inches). This forced the use of such high impact velocities (up to 660 ft/sec) that strong shock waves and cavitation of the water prevented smooth, continuous filling of the nozzle.

2. Specific energy values for single pulse craters in Barre granite varied from 8100 J/cc at a jet pressure of 113,000 psi to as low as 740 J/cc at a jet pressure of 250,000 psi. One data point yielded a specific energy of 223 J/cc at a pressure of 226,000 psi.

3. In most cases, the specific energy values obtained with vacuum in the American nozzle were higher than the prior results for atmospheric air pressure in the Russian nozzle.

8.0 RECOMMENDATIONS

Since jet stagnation pressures above 255,000 psi cannot be obtained easily using the existing nitrogen gas gun as an actuator, it is recommended that further testing on other types of rocks and with multiple pulses, which had been planned for Phase II, should not be attempted. The problem of piston damage with the existing test rig would make the research results unreliable. However, the test results indicate that further research and development should be conducted to evaluate the feasibility of pulsed water jets for rock tunneling. Such a program is now underway, sponsored by the U. S. Department of Transportation. It is recommended that primary emphasis be placed on test firings with air in the nozzle in order to achieve a practical machine.

REFERENCES

1. W. C. Cooley and P. E. Brockert, "Rock Disintegration by Pulsed Liquid Jets", Annual Report on Bureau of Mines Contract No. H0210012 by Terraspace Inc., January 31, 1972

2. W. C. Cooley and P. E. Brockert, "Design and Fabrication of Exponential Nozzle", Final Report on Bureau of Mines Contract No. H0210012 by Terraspace Inc,, March 31, 1972

PATENT STATEMENT

Terraspace certifies that no Subject Inventions have resulted from performance under this contract and that no sub-contracts were entered into containing a patents and inventions article.